Energy Efficiency in Hydraulics
Potential savings with valve-controlled linear actuators

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The term “hydraulic actuator” is misleading. A hydraulic actuator is nothing more or less than a transmission. To turn a hydraulic system into an “actuator”, some kind of energy carrier is required. The energy carrier is usually diesel fuel or electricity. Diesel fuel (primary energy) and electricity (secondary energy) are converted into rotation by means of an internal combustion engine or an electric motor respectively.

The rotation is then converted hydraulically into rotation at a different speed or into linear movement. The hydraulic transmission must be as efficient as possible. The efficiency of the hydraulic transmission is not the only important factor – attention must also be paid to the efficiency of the entire energy conversion chain from the energy carrier to the output.

The efficiency of a hydraulic system is the ratio of output power to input power. Losses occur in the hydraulic system as a result of the flow resistance of the fluid, leaks in the pump, motor and valve, mechanical friction loss in bearings, the oil used for hydrostatic pressure equalisation or the piloting of the valve and pump. The drive motor (diesel, electric motor) of the hydraulic transmission requires energy and has model-specific characteristic curves for efficiency. The energy requirement and efficiency of the drive motor are influenced by the arrangement of the hydraulic transmission. The hydraulic transmission partly determines the size of the drive motor (installed capacity) and it influences its duty point. This is why the efficient use of energy in hydraulics requires a global approach – the entire “hydraulic actuator”, consisting of the drive motor and the hydraulic transmission, must be designed to work well together, keeping losses to a minimum.

A great deal of attention has been paid to the energy efficiency of hydraulic transmissions for rotation. There are countless studies on the efficiency of various pump and motor types. At the moment, there is a lot of interest in the hydrostatic power unit for heavy diesel vehicles in stop and go operation. Recovered braking energy can be stored extremely well in light, hydraulic piston accumulators and re-used. The high power density of hydraulics is also an advantage in the piston accumulator: it can store larger quantities of energy in a shorter time than other technologies like batteries or capacitors, and it also weighs less.

Another function of the transmission is to convert the rotation into a hydraulic linear motion. Rotating gear wheels have virtually no power limit. Mechanical linear actuators quickly reach their limits due to the high load on the spindle nut material. Hydraulics leads the field here with the low-wear cylinder actuator. Hydraulic cylinder actuators are either pump-controlled or valve-controlled. The valve-controlled cylinder actuator is the more economical type. It is in widespread use and is normally supplied from a central hydraulic supply station because this spreads the cost of converting the energy carrier into hydraulic energy among several actuators. The “throttling control” of the valve-controlled linear actuator makes it less energy efficient than the pump-controlled type.
In the valve-controlled linear actuator, there is a great deal of scope for improving energy efficiency. We will consider the following possibilities for optimising the transmission.

- Increasing the power of electrically actuated valves
- Optimising the piloting of hydraulically actuated valves
- Optimising valve control for the cylinder economiser circuit

**Increasing the power of electrically actuated valves**

Hydraulically piloted valves (nominal size 100) are actuated by up to around 1MW of hydraulic power. Only around 100W of electrical input power is needed by electrically actuated pilot valves. The electric power needed to actuate the hydraulic system is negligible compared with the hydraulic input power. If the electrical force is no longer sufficient for direct actuation of valves, the hydraulic system uses its own strength and works with hydraulic piloting.

Piloted “on/off valves” do not use a large amount of energy to generate high actuation forces. After switching, the valves remain in their central or end positions. With the use of servo proportional valves, the situation changes subtly but decisively. Servo proportional valves do not remain in their end position but keep moving constantly, even if the movements are very small. No closed-loop control system would work without continual readjustment. The pilot valves alternate the flow of oil into the two opposing main-stage piston chambers. This produces a permanent delivery flow requirement. This flow of oil is either taken from the main conduit or is supplied from a separate control circuit. The maximum required pilot flow must be delivered at all times. At any time a rapid valve movement may be necessary. To achieve high control precision, the pistons of the servo proportional pilot valves have so-called “zero overlaps”. This generates additional leakage flows.

The state of the art for actuating a directly actuated servo proportional valve is the proportional solenoid. Gone are the days when people complained about the higher electrical input power compared with torque-motor-actuated flap- per-nozzle systems or jet-pipe systems. Such complaints were never justified from the point of view of energy. Piezo actuators could trigger further debate. Their power is not (yet) high enough for direct actuation, and hydraulic reinforcement is required as with the torque motor. Around 1kW of hydraulic power would be needed for the hydraulic actuation of the small piston of a directly actuated solenoid valve. The power requirement always depends on the diameter and stroke of the piston being piloted, and on the required dynamics. The hydraulic power requirement is significantly higher than for electric direct actuation. So from the point of view of energy efficiency, the question should not be “how much electric power does the valve need?”, rather “how much hydraulic power can the directly actuated valve control?” The higher its hydraulic power limit, the longer it is possible to dispense with hydraulic piloting. Piloted valves are usually modular products. The directly actuated valve is used as the pilot for piloted valves. The issues remains the same: “how much hydraulic power can the valve control? Is it sufficient for a large piloted valve?”

The hydraulic power requirement for piloting a large piloted valve can be very high, reaching several 100kW in a fast valve! If the power limit of a directly actuated valve is too low, either a number of valves are connected in parallel or an additional piloting stage is connected in between and the valve is operated in three stages. Both these solutions should be avoided as they increase the energy requirement.

Hydraulic systems often contain a large number of valves, frequently operating in standby mode for long periods even when the main circuit is not active, for example for safety reasons. The control power must be provided constantly. The difference in the energy balance between electrically actuated valves and hydraulically piloted valves is caused by the way in which the energy is provided. Electric power is held ready by the electricity network operator, and the valve electronics can access it on demand. Hydraulic power for piloting must be installed hydraulically, and then made available in a delivery process that is prone to serious losses. There is potential to improve energy efficiency because of the higher energy consumption of hydraulically piloted valves and the higher losses in delivering the power: higher-power, electrically actuated valves can replace hydraulically piloted valves.
As electrically actuated servo proportional valves become increasingly powerful, solenoid technology has reached its physical limits. Greater magnetic forces require larger coil windings. Large coils generate greater inductance. Greater inductance reduces the dynamics. The electrodynamic actuator principle (Voice Coil Drive), famous for good dynamics in speakers, can be used to improve the ratio of force to dynamics. If a number of actuator coils are placed in succession in magnetic fields, their forces are added together without limiting the dynamics to the same extent. This kind of electromagnetic converter can be used to construct actuators combining the dynamics of small torque-motor-actuated valves with the force of strong solenoids. This further shifts the power limit of directly actuated highly-dynamic valves towards higher pressures and greater volume flows. Although the potential saving of around 1 kW may not seem so high, the potential for the entire hydraulic system can be great because of the large number of valves of this type and because there is no longer any need to deliver energy.

**Optimising the piloting of hydraulically actuated valves**

If the force of the electric direct actuator is no longer sufficient to overcome the forces of acceleration, spring return and flow, the valve piston is actuated hydraulically using a pilot valve. The pressurised main piston front of a standard directional valve is determined from its piston dimensions. Countless studies into flow forces have shown that flow forces depend more on the piston diameter than on the piston surface area. A lot of hydraulic control energy is saved by adjusting the pressurised actuating surface to match the required actuation force, instead of simply making piloted valves larger. The piston diameter indicated during the design process by the nominal size does not have to be acted upon hydraulically over all its surface area.

A piloted standard directional valve (nominal size 10) does not have a hydraulic power limit for example. If a nominal size 10 is simply enlarged to a nominal size 100 valve, its piston diameter is five times larger and the piston surface area is 25 times larger. The setting force for each piston size increment increases by a factor of five. This oversizing leads to a pilot valve that is five times larger, with five times higher control energy consumption. The result is the parallel connection of multiple pilot actuators or a three-stage construction.

Energy-efficient designs use areas that are so small that even a valve with a large nominal size can be piloted by just one powerful valve with electric actuation. There generally need to be more piloted valves per system than directly actuated valves. On the other hand, the potential for energy savings per valve is significantly greater. Between 1 and 100 kW per piloted valve can be saved.
Optimising valve control for the cylinder economiser circuit

The machine design engineer often considers cylinders to be more mechanical components than hydraulic components. Because of its mechanical simplicity, the most widely used type by far is the differential cylinder. A differential cylinder consists of a piston rod and two actuation surfaces of different sizes. There are only two options for adjusting the cylinder to the needs of the system if the supply pressure remains constant (It is assumed that the supply system is shared among several actuators as is common practice.). The first is to determine the cylinder surface areas on the basis of the piston rod surface area. The second is a choice between two hydraulic circuits. The standard circuit works with all cylinder surface ratios and connects the cylinder sides alternately with the supply pressure or the tank. The regenerative circuit only works effectively from a cylinder surface ratio of around 2:1 (surface on piston side:surface on rod side). It returns the oil in the ring side back to the piston side as the cylinder moves out, reducing the amount of oil taken from the oil supply – which is why it is also called an “economiser circuit”. With regard to cylinder design, note that a cylinder only achieves its maximum force when it is stationary. As soon as it moves, the force is reduced by the portion of the supply pressure that is lost through throttling as a pressure drop at the valve. In an unloaded cylinder travelling at maximum speed, virtually all the energy introduced at the valve in the form of throttling losses is converted into heat. “Throttling control” works by regulating the introduction of energy by throttling, and it is precisely this characteristic that gives it great potential for improving energy efficiency.

Below, we will look at three widely-used typical cylinder designs and consider their potential for improving energy efficiency.

Case 1
A system requires different forces to extend and retract the cylinder. The extend force is greater than the retract force. One cylinder can be found with a surface area ratio precisely matching the ratio of forces. The remaining piston rods can introduce the force into the system without risk of buckling. The pressure losses in the standard directional valve with a standard circuit at maximum cylinder speed leave the cylinder with sufficient force to overcome the resistance in the system. The cylinder and circuit are optimised to work together and there is no opportunity to improve energy efficiency.

Case 2
A system requires the same forces to extend and retract the cylinder. Two combinations are possible. Version 1: a cylinder with a thin piston rod and a surface area ratio of 4:3 and a standard directional valve in a standard circuit. Version 2: a cylinder with a surface area ratio of 2:1 and a regenerative circuit. Version 2 requires a cylinder diameter around 20% larger than version 1 to achieve the same force. The installed pump capacity can be reduced by 75%, and 14% of the energy can be saved for an outward and return stroke.

Case 3
A system requires different forces to extend and retract the cylinder. The extend force is twice the retract force but is only required in full in the extended end position. Two combinations are possible. Version 1: a cylinder with a surface area ratio of 2:1 and a standard directional valve in a standard circuit. Version 2: a cylinder with a surface area ratio of 2:1 and a regenerative circuit, which switches to a standard circuit in the extended end position. Version 2 uses the same cylinder as version 1. The installed pump capacity can be reduced by 50%, and more than 30% of the energy can be saved for an outward and return stroke.

A 14 or 30% energy saving is possible – and the regenerative circuit has been around for a while. So why is it not seen more often in practical use? Searching the manufacturers’ catalogues for suitable components is usually a waste of time, ending up with warnings or time-consuming “do it yourself”.

The state of the art is a combination of a standard directional valve and two external check valves, returning the oil in the ring side through the pump connection (P-return) to the piston side (Cartridge valve circuits are not discussed here because of the wide range of options.) There is no longer a flow through one of the piston edges, turning the four-edge control into a three-edge control with familiar disadvantages in terms of regulation. There is a limit to the pulling loads that can be arrested as the ring side is always connected to the pump. The regeneration is active at all times.
Combining a servo proportional valve with four piston positions and an external check valve allows the connection between the ring side and the tank to be broken on a stroke-dependent basis, and the oil in the ring side to be returned through the pump connection (P-return) to the piston side. There are two versions. Version 1: without regeneration for a small stroke and with regeneration for a large stroke. Version 2: with regeneration for a small stroke and without regeneration for a large stroke.

A special piston in a standard directional valve allows permanent regeneration without an external check valve. The oil in the ring side is returned to the piston side within the valve through the pump connection (P-return). Because there is a throttling edge of the piston between the cylinder and the pump, the pressure of the rod side is always higher than the pressure of the pump. As a result of load-dependent pressure intensification, the rod side of the cylinder and the directional valve may be exposed to twice the pump pressure. In practice, there are safety implications that significantly limit the use of the permitted pressure of the components.

A special piston in a servo proportional valve with four piston positions allows the connection between the ring side and the tank to be broken on a stroke-dependent bases, and the oil on the ring side to be returned within the valve through the pump connection (P-return) to the piston side. Here, too, there are two versions with opposite orders. In this version with more piston positions, the problem of pressure intensification is even more critical as uninterrupted piston design is not possible.

Regeneration below the pump pressure is possible with a combination of a standard directional valve, an external check valve in the tank connection, and an external check valve returning the oil in the ring side directly to the piston side (A-return) instead of to the tank. This arrangement is of limited usefulness for control systems because the check valve has to be actuated for each change of direction. Oil is not returned if the tank connection is open.

All state-of-the-art solutions require external valves in addition to the standard directional valve. These may cause unwanted excess pressure in the cylinder or return oil on a speed-dependent basis, although energy can be saved at all speeds.

A new valve concept avoids all these disadvantages and provides a straightforward way of realising considerable potential savings in the valve-controlled linear actuator. A standard directional valve without additional valves returns the oil in the rod side through the A-connection to the piston side. The valve can be an on/off valve or a proportional/servo proportional valve with highly efficient four-edge control. Two versions are available: one works entirely regeneratively at all times, and the other – controlled by an electric signal – can switch between a regenerative circuit and a standard circuit. In both circuit modes, any speeds can be used. Switching can be made dependent on the required force, for example. If the force in the regenerative circuit is insufficient, the system switches to the standard circuit. This allows for the greatest possible energy savings. For example, in linear actuators, between 10 and 1000kW can be saved per cylinder.

There are considerable potential savings with all components in valve-controlled hydraulic cylinder actuators:

- Higher-power, electrically actuated valves can replace hydraulically piloted valves. Potential saving 1kW per actuator
- Large hydraulically actuated valves can dramatically reduce their hydraulic piloting power requirement by optimising piloting. One higher-power, electrically actuated valve is enough to pilot even the largest piloted valve. Potential saving between 1 and 100kW per actuator
- The oil requirement with partially-loaded cylinders can be reduced using a standard directional valve with an integrated A-regenerative economiser circuit. Switching between energy saving at partial load in the economiser circuit and high energy consumption at full load in the normal circuit can take place at any time independently of the piston stroke. Potential saving between 10 and 1000kW per actuator

Author: Dr.-Ing. G. Scheffel
General Manager of the Hydraulic Controls Division and Managing Director of Parker Hannifin Deutschland